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FORMING SAME

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ADHESIVE MICROSTRUCTURE AND METHOD OF FORMING SAME

5 This invention was made with Government support under Contract No. N660001-00-C-8047 awarded by Controlled Biological and Biomimetic Systems Program, DARPA, DSO, through a subcontract from iRobot Corp. The Government has certain rights to this invention.

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BRIEF DESCRIPTION OF THE INVENTION

This invention relates generally to the fabrication and utilization of micron-scale structures. More particularly, this invention relates to a fabricated adhesive

15 microstructure.

BACKGROUND OF THE INVENTION

There is an ongoing need for improved adhesives. Improved adhesives have applications ranging from everyday aspects of life (e.g., tape, fasteners, and toys) to high technology (e.g., removal of microscopic particles from semiconductor wafers, transporting fiber optic devices, and assembly of sub-mm mechanisms, particularly those including micro-fabricated components, or components that cannot tolerate regular grippers, adhesives, or vacuum manipulators).

Adhesive mechanisms in nature have been studied, but have not been fully understood or exploited. For example, Geckos are exceptional in their ability to rapidly climb up smooth vertical surfaces. The mechanism of adhesion used in Geckos,

Anolis lizards, some skinks, and some insects, has been debated for nearly a century.

While some prior work has identified the morphology of seta used by Geckos and other insects, this prior work does 5 not identify how the seta operates. In addition, this prior work fails to identify how to use a seta to perform useful work.

It would be highly desirable to identify and exploit the adhesive force mechanism utilized by Geckos and other insects. 10 Such information could result in the utilization of new adhesive microstructures and the fabrication of such structures.

SUMMARY OF THE INVENTION

15 In one aspect, an embodiment of the invention features a fabricated microstructure. The microstructure comprises a plurality of protrusions. Each protrusion is capable of providing a substantially parallel adhesive force at a surface of between about 60 and 2000 nano-Newton. A flexible shaft 20 supports the protrusions, and the shaft is attached to a flexible beam.

Various implementations of the invention may include one or more of the following features. There are a plurality of shafts attached to the flexible beam, with each of the shafts 25 supporting a plurality of protrusions. The shaft has a length of less than about 500 microns, and a diameter between about 0.01 and 0.1 times the length of the shaft. The shaft has a diameter of about 0.05 times the length of the shaft. The shaft has a length of between about 10 and 100 microns. The 30 protrusions adhere to the surface by intermolecular forces.

The flexible beam has a length of between about 1 and 5 centimeters, a width of between about 0.5 and 1 centimeter, and a thickness of between about 0.1 and 0.3 millimeters. The flexible beam produces between about 0.01 and 0.10 grams of a 5 preload force while maintaining a substantially parallel alignment of the protrusions with a surface.

In another aspect, an embodiment of the invention features a fabricated microstructure comprising an array of protrusions. The array has a width less than about ten 10 microns and each protrusion is capable of providing an adhesive force at a surface by intermolecular forces. A shaft supports the array, and the shaft is attached to a flexible beam.

In another aspect, an embodiment of the invention 15 features a fabricated grip. The grip comprises a lamella from a specimen attached to a flexible beam and configured to engage an item to be manipulated.

Various implementations of the invention may include one or more of the following features. A substrate may be 20 provided to support an object wherein the lamella is attachable to the substrate to manipulate the object.

In still another aspect, an embodiment of the invention features a fabricated microstructure comprising a shaft with a length of less than about 500 microns. The shaft has a 25 diameter of between about 0.01 and 0.1 times its length. An array of spatulae are formed at the end of the shaft. The array has a width of less than about ten microns. Individual spatula of the array have a terminal end to provide an adhesive force at a surface. The shaft is attached to a 30 flexible beam.

Various implementations of the invention may include one or more of the following features. The shaft has a length of between approximately 10 and 100 microns. The shaft has a diameter of approximately 0.05 times its length. The terminal 5 end of an individual spatula has a radius of approximately 2 microns. The flexible beam has a length of between about 1 and 5 centimeters, a width of between 0.5 and 1 centimeter, and a thickness of between 0.1 and 0.3 millimeters. The flexible beam produces between about 0.01 and 0.10 grams of 10 the preload force while maintaining substantially parallel alignment of the array of spatulae with the surface. The terminal end of an individual spatula has a shape selected from the group consisting of a curved segment of a sphere, a flattened segment of a sphere, a sphere and a flattened 15 surface.

In another aspect, an embodiment of the invention features a method of forming an adhesive force. The method comprises attaching a seta from a specimen to a flexible beam. The seta is applied to a surface so as to establish an 20 adhesive force at the surface so the flexible beam can be used to manipulate an object.

Various implementations of the invention may include one or more of the following features. The method may further include removing a seta from a gecko. The method may also 25 include removing a seta from a living specimen selected from the group consisting of species of *Anolis*, skinks, beetles and kissing bugs. The applying step of the method may include applying the seta to the surface with a force perpendicular to the surface, and pulling the seta with a force parallel to the 30 surface so as to engage the adhesive force. The adhesive

force is greater than the cumulative force of the applying and pulling steps.

In still another aspect, an embodiment of the invention features a method of establishing an adhesive force comprising 5 using a flexible beam to apply a seta to a surface with a force perpendicular to the surface so as to preload an adhesive force of the seta. A flexible beam is used to orient the seta parallel to the surface and pull the seta with a force parallel to the surface.

10 Various implementations of the invention may include one or more of the following features. The adhesive force is greater than the cumulative force of the applying and pulling steps. The method may further comprise eliminating the adhesive force by creating a force to produce a detachment 15 angle between the seta and the surface. The eliminating step includes a step of creating a force to produce a detachment angle of between about 25° and 35° between the seta and the surface. The eliminating step includes creating a force to produce a detachment angle of approximately 30° between the 20 seta and the surface. The flexible beam produces between about 0.01 and 0.10 grams of a preload force while maintaining a substantially parallel alignment of the seta with the surface.

25 In another aspect, an embodiment of the invention features a method of fabricating an adhesive microstructure. The method comprises fabricating an array of shafts, forming spatulae on the array of shafts, and attaching the array of shafts to a flexible member.

30 Various implementations of the invention may include one or more of the following features. The forming step includes the step of forming spatulae, wherein the terminal end of

individual spatula of the spatulae include an extended surface. The forming step includes the steps of constructing spatulae and attaching the spatulae to the array of shafts.

In still another aspect, an embodiment of the invention 5 features a method of fabricating an adhesive microstructure comprising contacting a seta of a specimen with a semiconductor substrate and causing relative motion between the seta and the semiconductor substrate to remove the seta from the specimen. The removed seta is attached to a flexible 10 beam so the flexible beam can be used to manipulate an object.

In yet another aspect, an embodiment of the invention features a method of establishing an adhesive force. The method comprises using a flexible beam to apply a seta to a surface with a force perpendicular to the surface so as to 15 preload an adhesive of the seta, and using the flexible beam to orient the seta parallel to the surface. The flexible beam is then used to pull the seta at a velocity to increase the adhesive force exerted by the seta on the surface.

Various implementations of the invention may include one 20 or more of the following features. The semiconductor substrate is a silicon or gallium arsenide wafer. The flexible beam is made from the material selected from the group consisting of acetate, nylon, acrylic, brass and spring steel.

25 Certain embodiments of the invention can include one or more of the following advantages. A fabricated microstructure provides an improved device for manipulating objects. The microstructure is relatively inexpensive to produce.

30 The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects and advantages of the

invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

5 For a better understanding of the invention, reference should be made to the following detailed description taken in conjunction with the accompanying drawings, in which:

FIGURE 1A illustrates preloading operations performed in accordance with an embodiment of the invention.

10 FIGURE 1B illustrates rows of setae used in accordance with the invention.

FIGURE 1C illustrates a single seta used in accordance with the invention.

15 FIGURE 1D is an enlarged view of a single seta used in accordance with an embodiment of the invention.

FIGURE 1E is an enlarged view of a single extended surface spatula on a spatula stalk, in accordance with an embodiment of the invention.

20 FIGURE 1F is an enlarged view of a single extended surface spatula on a spatula stalk, in accordance with an embodiment of the invention.

FIGURE 1G illustrates an array of spatulae formed at the end of a shaft to form seta used in accordance with the invention.

25 FIGURE 1H illustrates a system to measure adhesive force achieved in accordance with the invention.

FIGURE 1I is another illustration of a system to measure adhesive force achieved in accordance with the invention.

FIGURES 2A-2B illustrate different forces, as a function of time, associated with the loading and adhesion operation of a structure of the invention.

5 FIGURE 3 illustrates perpendicular preload force associated with an embodiment of the invention.

FIGURE 4 illustrates perpendicular force during detachment of a structure utilized in accordance with the invention.

10 FIGURES 5A-5C illustrate the fabrication of an array of setae with spatula structures in accordance with an oxide/nitride fabrication process utilized in accordance with an embodiment of the invention.

15 FIGURES 6A-6B illustrate the fabrication of an array of setae in accordance with an excitation source process utilized in accordance with an embodiment of the invention.

FIGURE 7 illustrates the fabrication of an array of setae with spatula structures in accordance with a stalk and seeding process utilized in accordance with an embodiment of the invention.

20 FIGURE 8 illustrates the fabrication of a single spatula using a micro-pipette.

FIGURE 9 illustrates an embossing tool used to form a spatulae mold for use in accordance with an embodiment of the invention.

25 FIGURES 10A-10D illustrate lithographically induced self-construction of spatulae in accordance with an embodiment of the invention.

FIGURES 11A-11B illustrate a roller nano-imprinting technique that may be used to form spatulae in accordance with 30 an embodiment of the invention.

FIGURE 12 illustrates a two-layer photoresist fabrication technique that may be used in accordance with an embodiment of the invention.

FIGURE 13 illustrates a setae-based manipulator that may 5 be used in accordance with an embodiment of the invention.

FIGURE 14A is a schematic side view illustrating a seta-based manipulator having a flexible member or beam.

FIGURE 14B is a view along line 14B - 14B of FIGURE 14A.

FIGURES 15A and 15B schematically illustrate a technique 10 for harvesting a seta structure from a specimen.

FIGURES 16A and 16B are schematic perspective and side views, respectively, of an arrangement for manipulating an object.

FIGURE 17 graphically illustrates the adhesive frictional 15 force of an isolated gecko setal array moving relative to a surface.

FIGURE 18 graphically illustrates frictional adhesive force versus parallel sliding velocity for different gecko setal arrays.

20 Like reference numerals refer to corresponding parts throughout the drawings.

DETAILED DESCRIPTION OF THE INVENTION

The invention is directed toward the use of micron scale 25 structures to achieve adhesion. In particular, the invention uses a seta structure. The seta structure has a shaft. Positioned at the end of the shaft is a spatula or an array of spatulae. Adhesion is produced as the spatula or array of spatulae produce intimate contact with a surface.

30 In general, the shaft is between 1 and 500 microns long, preferably approximately 10 to 100 microns long. The diameter

of the shaft is preferably between 0.01 and 0.1 times the length of the shaft, preferably approximately 0.05 times the length of the shaft.

The terminal end of the shaft has at least one spatula.

5 Preferably, the terminal end of the shaft has between 1 and 1000 spatulae. The array of spatulae is preferably less than 10 microns wide, preferably approximately 1 micron wide. Preferably, each spatula of the array of spatulae has an extended surface at its terminal end. The extended surface
10 may be in the form of a paddle or a curved segment of a sphere, as shown below.

The structure of the invention is modeled from structures found in nature, such as the seta found on the foot of a Tokay gecko (*Gekko gecko*). Many species of gecko (e.g., clade
15 Gekkonoidea), species of *Anolis*, and several skink species have adhesive setae that may also be used in accordance with the invention. In addition, beetles and kissing-bugs have setae that may be used in accordance with the invention. The invention is implemented with natural or fabricated setae, as
20 discussed below.

Examples of seta structures found in nature follow. The seta of a Tokay Gecko has a stalk (shaft) diameter of 5μ , a stalk height of 110μ , a tip (spatulae) length of 0.2μ , a tip width of 0.2μ , and between 100-1000 tips, where the total tip
25 area per stalk is 2 to $20\mu^2$. *Anolis cuvieri* has a stalk diameter of 0.5μ , a stalk height of 22μ , a tip length of 0.6μ , a tip width of 0.7μ , and between 100-1000 tips, where the total tip area per stalk is 2 to $20\mu^2$. *Prasinohaema virens* (skink) has a stalk diameter of 2μ , a stalk height of 26μ , a
30 tip length of 6μ , a tip width of 7μ , and between 100-1000

tips, where the total tip area per stalk is approximately $20\mu^2$.

By way of example, Figure 1A illustrates a Tokay gecko 20 with terminal limbs 21 that have naturally occurring setae.

5 The live gecko 20 is restrained. A cuticular layer portion, for example, a lamella or scisor, of a terminal limb (e.g., a toe) 21 is removed. This operation, analogous to cutting hair, allows the gecko to harmlessly regenerate its setae. It has been demonstrated that hundreds or thousands of setae can
10 be easily harvested without sacrificing the living being from which the setae are removed.

After removal, the cuticular surface is scraped to break off individual seta, preferably at the base of the shaft of the seta. Figure 1B illustrates rows 22 of setae associated with the gecko 20. Figure 1C illustrates the shaft 24 of a single seta 26. The figure also illustrates the spatulae 28 positioned at the end of the shaft 24.

Figure 1D is an enlarged view of a single seta 26. The figure illustrates that the shaft 24 is roughly perpendicular to the spatulae 28.

Figure 1E is an enlarged view of a single spatula 29 on a spatula stalk 30. The spatula stalk 30 may be the shaft 24 or a separate tendril extending from the shaft 24. Preferably, each spatula 29 has an extended surface. In Figure 1E, the 25 extended surface is in the form of a paddle structure. In Figure 1F, the extended surface is in the form of a sphere. Figure 1G is an enlarged view of an array of spatulae 28.

The realization of large adhesive forces by the setae is contingent upon preload operations performed in accordance with the invention. Detachment of the setae occurs at a characteristic angle, as specified in accordance with the

invention. Figure 1H illustrates a substrate (i,e., a sensor 32) that was used to characterize these forces. Figure 1I illustrates the characteristic angle (α) for detaching setae of the invention. The characteristic angle (α) is formed 5 between the seta 26 and a surface 40 to which the seta is attached.

The inventors have identified that the adhesive force of a seta depends upon its three-dimensional orientation (spatulae pointing toward or away from the surface) and the 10 extent to which the seta is preloaded (pushed into and pulled along the surface) during initial contact. Contacting the surface with the seta in a direction other than with spatulae projecting toward the surface resulted in forces less than 0.3 μ N when the seta was pulled away perpendicular to the surface. 15 A pull parallel to the surface showed that the force produced by the inactive, non-spatular region increased with a normal or perpendicular force, typical of a material with a coefficient of friction equal to 0.2. By contrast, when the active spatular region was projecting toward the surface, the 20 force increased by 20 to 60-fold. The force resulting from pulling the seta parallel to the surface during attachment increased when setae were first pushed toward the surface, providing a perpendicular preloading force. This initial perpendicular force need not be maintained during the 25 subsequent pull. Setal force parallel to the surface increased linearly with the perpendicular preloading force.

Experiments in which seta were pulled away from the surface of a wire demonstrated that perpendicular preloading alone is insufficient to prevent the seta from being dislodged 30 easily. Seta that were first pushed into the surface and then pulled parallel to it developed over ten times the force (13.6

$\mu\text{N} \pm 2.6 \text{ SD}$; $N = 17$) upon being pulled away from the surface than those having only a perpendicular preload ($0.6 \mu\text{N} \pm 0.7 \text{ SD}$; $N = 17$). The largest parallel forces were observed only following a few microns of sliding. The results of preloading 5 on setal force production suggest that a small perpendicular preloading force in concert with a rearward displacement or parallel preload may be necessary to "engage" adhesion. Preloading is believed to increase the number of spatulae contacting the surface.

10 The orientation of the setae is also important in detachment. The force produced when a seta was pulled away from the surface was not significantly differently from the force measured during a pull parallel to the surface if the same perpendicular preload was given. However, it has been 15 identified that setae detached at a similar angle ($30.6^\circ \pm 1.8 \text{ SD}$; $N = 17$) and force when pulled away from the sensor's surface. To check for the presence of a critical angle of detachment, the perpendicular force was held constant, while the setal angle was progressively increased until detachment. 20 Setal angle at detachment changed by only 15% over a range of perpendicular forces. Thus, the invention uses a detachment angle of between about 35° and 25° , preferably approximately 30° . The detachment angle values are based upon the disclosed seta structure in which the shaft of the seta is roughly 25 perpendicular to the spatular surface, as shown in Figure 1D. Change in the orientation of the setae and perhaps even the geometry of the spatulae may facilitate detachment.

The foot of a Tokay gecko (*Gekko gecko*) holds approximately $5000 \text{ setae mm}^{-2}$ and can produce 10 N of adhesive 30 force with approximately 100 mm^2 of pad area. Therefore, each seta should produce an average force of $20 \mu\text{N}$ and an

average stress of 0.1 N mm⁻² (~1 atm). The actual magnitudes are probably greater, since it is unlikely that all setae adhere simultaneously.

The foregoing information is more fully appreciated in connection with specific operations performed in accordance with the invention. An isolated seta, secured by the technique discussed above, was glued to a substrate (e.g., to the end of a #2 insect pin) with epoxy (e.g., 5-MINUTE EPOXY sold by TTWDevcon, Danvers, MA). The pin had a diameter of approximately 15 μ m. To prevent the epoxy from creeping up the stalk of the seta, which might change the mechanical property of the specimen, the epoxy is preferably precured for approximately 1 minute before applying it to the specimen. All setae were oriented such that the active surface was approximately perpendicular to the axis of the pin. All preparations were completed under a compound microscope.

Force production by single, isolated seta during attachment was measured using a micromachined, dual-axis, piezoresistive sensor 32 of the type illustrated in Figure 1H. The following discussion provides information with respect to the sensor 32. U.S. Patent 5,959,200 describes a sensor of the type described herein. The sensor 32 does not form a part of the invention, rather it is merely used to obtain the performance results described below.

The cantilever sensor 32 of Figure 1H was fabricated on a single-crystalline silicon wafer. The cantilever 32 has two independent force sensors, each with one predominant direction of compliance. The perpendicular force sensor consists of a thin triangular probe 50. The parallel force sensor is composed of four long slender ribs 52. A special 45° oblique ion implantation allowed piezoresistive and

conductive regions to be implanted on both the parallel and perpendicular surfaces simultaneously. Forces applied to the tip of the sensor were resolved into these two orthogonal directions (parallel and perpendicular), and were measured by 5 the changes in resistance of the piezoresistors. Since this device was originally designed for Atomic Force Microscope data storage applications, each of these cantilever devices had a sharp tip near the vertex of its triangular probe. For the gecko setae adhesion measurement, the back-side of this 10 device was used to provide a smooth surface for setal adhesion.

Each seta 26 was brought in contact with the sensor 32 by applying a small preload perpendicular to the surface to increase contact and induce adhesion. To determine the effect 15 of preload force on submaximal parallel force, preload force was varied when setae were attached to the tip of the sensor, as shown in Figure 3, which is discussed below. To measure maximal parallel force, the base of the triangular probe was used. Using the base increased area of contact, but did not 20 allow for simultaneous measurement of preload forces. Sensor signals were taken while the seta was being pulled parallel to the surface by a piezoelectric manipulator at a rate of $\sim 5 \mu\text{m sec}^{-1}$. Sensor signals were amplified and filtered through a 300-Hz low-pass filter, and then digitized at 100 Hz using a 25 16-bit data acquisition card (LabView™ on a PC). The collected data (in volts) were converted to deflections of the sensor through calibration constants, and multiplied by the stiffness of the cantilever to obtain force values.

Breaking or detachment force was defined as the maximal 30 force a seta could exert perpendicular, or normal, to a surface immediately before it released. This value was

determined for individual seta by measuring the amount it could displace a force gauge made from a 4.7 mm aluminum bonding wire with 25 μ m nominal diameter (American Fine Wire Corp., Selma, AL; the wire 40 is shown in Figure 1I). To 5 maximize contact area of the active surface of the seta to the wire, a 50 μ m x 100 μ m section of the wire tip was flattened. The proximal end of the wire was fixed with epoxy onto a brass stub. The active surface of the seta was pressed against the flattened wire, producing a known perpendicular preload 10 (1.6 \pm 0.25 μ N; mean \pm SD). The force was measured using two different methods of detachment: (1) the seta was pulled normal to the wire; and (2) the insect pin was displaced 19.7 \pm 3.45 μ m along the wire to produce an additional parallel preload on the seta before pulling perpendicular or normal to 15 the wire.

In all trials, detachment force was calculated from the maximum displacement of the wire pulled by the seta. All sequences were recorded with a video camera (e.g., a CCD camera sold by SONY) and digitized to a computer (e.g., an 20 APPLE, MACINTOSH) using a video editing system (e.g., from MEDIA 100 Inc., Marlboro, MA). The initial position of the wire, the angle of the seta with respect to the wire and the position of the wire at the point of separation were recorded and analyzed using image analysis software (e.g., NIH-Image 25 software). The amount of deflection in the force gauge was converted to adhesion force after the force gauge was calibrated against standard weights.

The results of these operations are shown in Figures 2-4. Figure 2A illustrates forces associated with a perpendicular 30 preload and a subsequent parallel pulling performed in accordance with the invention. As shown in Figure 2A, setal

adhesive force parallel to the surface increased linearly until the seta began to slide off the edge of the sensor at time t_s . If the seta was allowed to slide approximately 5 μm along the sensor's surface, a distance imperceptible at the 5 level of the foot, adhesive force continued to increase, as shown in Figure 2B. The maximum adhesive force of single seta averaged $194 \mu\text{N} \pm 25 \text{ SD}$ ($N = 28$), nearly 10-fold greater than predicted from whole animal estimates.

As can also be seen from Figure 2B, the force varied from 10 approximately 60 to 200 micro-Newton (μN). As noted, a seta may include between 100 and 1,000 spatulae. Thus, the force provided by each spatulae is between about .06 to $2\mu\text{N}$, or between about 60 and 2,000 nano-Newton.

The single-seta force measurements suggest that if all 15 setae were simultaneously and maximally attached, a single foot of a gecko could produce 100 N of adhesive force (-10 arm). Stated another way, the foot of a gecko could generate maximum observed force (10 N) with only 10% of its setae maximally attached.

20 The maximum force developed by a given seta could not be predicted from molecular interactions or microscopic anatomy alone. Setal force depended on its three-dimensional orientation (spatulae pointing toward or away from the surface) and the extent to which the hair was preloaded (i.e., 25 pushed into and pulled along the surface) during initial contact. Contacting the surface with the seta in a direction other than with spatulae projecting toward the surface resulted in forces less than 0.3 μN when the seta was pulled away perpendicular to the surface. A pull parallel to the 30 surface showed that the force produced by the inactive, non-spatular region increased with a normal or perpendicular

force, typical of a material with a coefficient of friction equal to 0.25, see Figure 3. By contrast, when the active spatular region was projecting toward the surface, force increased by 20 to 60-fold. The force resulting from pulling 5 the seta parallel to the surface during attachment increased when setae were first pushed toward the surface providing a perpendicular preloading force, shown in Figure 2A. This initial perpendicular force need not be maintained during the subsequent pull. Setal force parallel to the surface increased 10 linearly with the perpendicular preloading force, as shown in Figure 3. Experiments in which seta were pulled away from a surface (e.g., surface 40, a wire in Figure 1F) demonstrated that perpendicular preloading alone is insufficient to prevent the seta from being dislodged easily. Seta that were first 15 pushed into the surface and then pulled parallel to it developed over ten times the force ($13.6 \mu\text{N} \pm 2.6 \text{ SD}$; $N = 17$) upon being pulled away from the surface than those having only a perpendicular preload ($0.6 \mu\text{N} \pm 0.7 \text{ SD}$; $N = 17$). The largest parallel forces were observed only following a few 20 microns of sliding, as shown in Figure 2B.

The results of preloading on setal force production support the hypothesis that a small perpendicular preloading force in concert with a rearward displacement or parallel preload may be necessary to "engage" adhesion. Since the tips 25 of the setae are directed rearwards away from the toenail, preloading may increase the number of spatulae contacting the surface.

The orientation of the setae also appears to be important in detachment during locomotion. The force produced when a 30 seta was pulled away from the surface was not significantly different from the force measured during a pull parallel to

the surface if the same perpendicular preload was given. However, it was identified that setae detached at a similar angle ($30.6^\circ \pm 1.8$ SD; $N = 17$) when pulled away from the wire sensor's surface. To check for the presence of a critical angle of detachment, perpendicular force was held constant, while the setal angle (α ; Figure 1F) progressively increased until detachment. Setal angle at detachment changed by only 15% over a range of perpendicular forces, as shown in Figure 4. This observation is consistent with an adhesive model where sliding stops when pulling at greater than the critical setal angle and hence stress can increase at a boundary, causing fracture of the contact. Change in the orientation of the setae and perhaps even the geometry of the spatulae may facilitate detachment.

It has long been known that geckos peel the tips of their toes away from a smooth surface during running. Toe peeling may have two effects. First, it may put an individual seta in an orientation or at a critical angle that aids in its release. Second, toe peeling concentrates the detachment force on only a small subset of all attached setae at any instant. The toe peeling behavior is analogous to the technique used by humans to remove a piece of tape from a surface.

The direct setal force measurements are consistent with the hypothesis that adhesion in geckos is the result of intermolecular forces. The simple models available can only give the most approximate estimates of setal force production. If it is assumed that the tip of a spatula is a curved segment of a sphere (radius, $R = 2\mu\text{m}$) and is separated by a small distance from a large, flat surface where van der Waals forces become significant (atomic gap distance, $D \approx 0.3$ nm), then

setal force = $AR / 6D^2$, where A is the material dependent Hamaker constant taken to be 10^{-19} J¹⁰. This estimate puts the van der Waals force for a spatula to be about 0.4 μ N. Since the number of spatula per seta varies from 100 to 1000, setal force estimates range from 40 to 400 μ N.

Earlier experimental support for the van der Waals hypothesis comes from the observation that adhesive force of a whole gecko increases with increasing surface energy of the substrate. In addition, the rejection of alternative mechanisms such as suction, electrostatics, friction, microinterlocking, and wet adhesion, has been attempted. Adhesion experiments carried out in a vacuum and the disclosed measurements of greater than one atmosphere of adhesion pressure strongly suggest that suction is not involved. Experiments using X-ray bombardment eliminates electrostatic attraction as a mechanism necessary for setal adhesion, since the setae can still adhere in ionized air. Microinterlocking could function as a secondary mechanism, but the ability of geckos to adhere to polished glass shows that irregularities on the scale of the spatulae are not necessary for adhesion. The findings herein do not support a friction mechanism because the cantilever's surface is smooth (surface roughness less than or equal to 2.5 nm) and the coefficient of friction of the setal keratin on silicon is low ($\mu = 0.25$; Fig. 3; dashed line). Capillary adhesion or glue are not likely mechanisms, since skin glands are not present on the feet of lizards. The mechanism of adhesion may involve a thin layer of water, or adsorbed water molecules on the seta and/or substrate.

Van der Waals forces are extremely weak at greater than atomic distance gaps, and require intimate contact between the

adhesive and the surface. Polymeric adhesives such as tape are soft, and are able to deform sufficiently for intimate contact over a relatively large surface area. The feet of a Tokay gecko (*Gekko gecko*) contain approximately one billion 5 spatulae that appear to provide a sufficiently large surface area in close contact with the substrate for adhesion to be the result of van der Waals forces.

As previously indicated, the invention may be used in connection with setae harvested from a live specimen.

10 Alternately, the techniques of the invention may be used in connection with fabricated setae. Those skilled in the art will recognize a number of techniques that may be used to fabricate setae in accordance with the invention. For example, the devices may be fabricated through an 15 oxide/nitride process, as shown in Figures 5A-5C.

Initially, a recess is etched in a semiconductor substrate. Figure 5A illustrates a recess 101 formed in a semiconductor substrate 100. Nitride and oxide layers are then deposited on the substrate 100. Figure 5A illustrates a 20 nitride layer 102 and an oxide layer 104. The surface is then patterned and etched, resulting in the structure of Figure 5B.

Afterwards, the underlying substrate 100 is etched, resulting in a well 106, as shown in Figure 5C. At this point, the stress difference between the oxide and nitride 25 layers causes the structure to curl from the plane defined by the substrate 100, thereby forming a shaft structure. The end of the shaft may then be roughened to form spatulae. For example, the spatulae may be formed by wet etching, radiation, plasma roughening, electro-chemical etching, and the like. 30 Alternately, a separate spatulae may be affixed to the shaft. Techniques for fabricating spatulae are discussed below.

Another technique that may be utilized in accordance with the invention exploits an excitation source. As shown in Figure 6A, a sensitive material 122 is formed on a substrate 120. An excitation source 124 is used to apply excitation energy to the sensitive material 122. The deep-penetrating excitation alters the volume along the trajectory of excitation. The altered volume is then selectively etched away. This results in a tube 126, as shown in Figure 6B. At higher densities of exposure, the remaining material becomes a random array of isolated fingers. The end of each tube 126 is then processed to form spatulae or spatulae that are attached to the tubes.

Figure 7 illustrates another technique that may be utilized in accordance with the invention. This embodiment 15 relies upon the deposition of an etchable material on a substrate 130. Stalks 132 are then patterned and etched from the etchable material. The etched substrate may be coated with oxide and/or nitride layers. Alternately, polymer layers may be used as a coating. The polymer layers may be spin- 20 cast, using materials, such as photoresist, polyimide, glass, or epoxy-based compounds. The resultant stalks 132 are then seeded to form nanotubes 136, operating as spatulae.

Artificial spatulae may be formed using a glass micro-pipette drawn down to a narrow aperture (e.g., 500 nm) at an 25 end. Liquid polymer is extruded through the hollow pipette and is then cured. Surface tension creates a hemispherical drop at the end of the pipette. Figure 8 illustrates this technique. In particular, the figure illustrates a micro-pipette 150 with a liquid polymer 152 positioned therein to 30 form a hemispherical drop 154.

Materials that can be applied to the micro-pipette include low viscosity ultra violet cure epoxy, uncured silicone rubber, or polyurethane resin. The hemisphere at the end of the micro-pipette can be flattened or embossed by 5 pressing against a polished surface. A flattened surface, such as the paddle structure of Figure 1E, with its larger contact area, has better adhesive properties than a sphere.

The single spatula pipette can be used as an embossing tool to make a nano-mold by plastically deforming a material, 10 such as molten polystyrene. A large area mold (e.g., 20 by 20 microns) can be formed by either step-and-repeat embossing or by making an array of pipettes and embossing a large pattern.

Figure 9 illustrates an array of pipettes used to form an embossing tool 160. The embossing tool 160 is applied to a 15 polystyrene material 162 positioned on a substrate 164. This results in a patterned polystyrene surface 166.

Alternatively, a nano-channel glass, which consists of a large bundle of hollow glass fibers, can be used. The nano-channel glass can be filled with a polymer, and then the glass 20 can be dissolved in an acid.

Spatulae may also be formed by lithographically induced self construction. With this technique, electrostatic attraction is used to pull liquid through a mask, and thereby "sprout" spatulae. This process is shown in connection with 25 Figures 10A-10D.

Figure 10A illustrates a growing layer 170 positioned on a substrate 172. The growing layer may be molten polymer or thermoplastic. Spacers 174 are positioned on the substrate 172 and a mask 176 is constructed on the spacers 174. The 30 growing layer 170 is electrostatically attracted to the upper mask layer 176, producing a set of protrusions 178, as shown

in Figure 10C. The resultant spatulae array is shown in Figure 10D.

Stalks and spatulae may also be formed from a mold using a nano-imprinting roller. This technique is shown in 5 connection with Figures 11A-11B. While nano-imprinting techniques of the type shown in Figures 11A-11B have been used in the prior art, they have not been used to produce spatulae structures.

Figure 12 illustrates that a 2-layer photoresists can be 10 formed with different resist exposure sensitivities, so that the upper layer forms, for example, 100 nm square plates that are supported by much longer and thinner pedestals. Standing-wave interference patterns can be used to expose and pattern features to fabricate large area arrays. Similar structures 15 can be made with SiO_x layers on silicon substrates by plasma etching.

Setae shafts may be fabricated using a sandwich of polymer layers. A polymer layer can include spin-cast polymer materials, such as photoresist, polyimide, glass, or epoxy- 20 based compounds. A polymer layer can also include spray-deposited polymer materials, such as photoresist, polyimide, glass, or epoxy-based compounds. Alternately, a polymer layer may be an ultra-violet curable epoxy.

Figure 13 illustrates a manipulator 200 formed in 25 accordance with an embodiment of the invention. The manipulator 200 includes a beam 202 with a set of setae 26A-26D arranged in opposing pairs (e.g., 26A and 26C oppose one another, as do 26B and 26D). The beam 202 is pushed toward the substrate 204 to preload and spread the setae 26A-26D. 30 The beam 202 is then pulled away from the substrate 204 to

drag and pick-up the substrate 204. The beam 202 is pushed toward the substrate 204 to release the setae 26A-26D.

Figures 14A and 14B show a grip or manipulator 300 made in accordance with an embodiment of the invention. The grip 5 300 includes a flexible beam or member 302 having a seta structure 304 formed at its end 302a. As discussed, the seta structure includes a shaft having at least one spatula or an array of spatulae at the end of the shaft.

The beam 302 is flexible to control preload and 10 orientation of the grip 300. That is, in operation, a face 304a of the seta structure 304 is pushed by means of the flexible beam 302 toward and into contact with an object to be manipulated to preload and spread the seta structure 304. The flexible beam 302 is then pulled away from the object to drag 15 and pick it up. The flexible beam 302 is pushed toward the object to release the setae.

The beam 302 is made of a flexible material such as acetate, nylon, acrylic, brass, or spring steel. The stiffness of the beam 302 should be set to produce 20 approximately 0.01 grams to 0.1 grams of a preload force while maintaining substantially parallel alignment of the seta structure 304 with a surface or object.

The seta structure 304 may be adhered to the beam end 302a by an appropriate adhesive such as the 5-MINUTE EPOXY 25 noted above. The beam 302, in one configuration, may have a length L of between about one and five centimeters (cm), a width W of between about 0.5 and one cm, and a thickness T of between about 0.1 and 0.3 millimeters (mm).

The seta structure 304 may be fabricated as noted above. 30 Alternatively, it may be harvested from a specimen such as the foot of a Tokay gecko. Specifically, as shown in Figures 15A

and 15B, a live gecko is restrained and a portion of a terminal limb (e.g., a toe) 21 is dragged or pulled across a surface 400 of a semiconductor substrate 402. The substrate 402, for example, may be a silicon or gallium arsenide wafer.

5 An entire lamella 404 may be isolated from the gecko's toe. The lamella, with gecko skin 406 attached, remains on the surface 400 of the semiconductor substrate 402. As discussed above, this operation allows the lamella to be removed from a gecko's limb without harming the gecko. The 10 gecko also harmlessly regenerates its setae. The isolated lamella can then be adhered, as discussed, to the end 302a of the beam 302. The lamella, in this configuration, forms the seta structure 304.

The manipulator 300 may be used to manipulate an object 15 by appropriately loading the seta structure against a surface of the object. Also, as shown in Figures 16A and 16B, the manipulator 300 may be used to lift, for instance, an object 500 which is attached to a glass substrate or coverslip 502 by a wire 504. The wire 504 may be a steel wire with a nominal 20 diameter of about 0.2 mm.

The seta structure 304 of the manipulator 300 can be loaded against an underside 502a of the coverslip to manipulate the object by application of a force F . The end 302b of the beam 302 may be held by a pin clamp. The angle θ 25 between formed between the position of the coverslip and horizontal may be about 45 degrees.

A manipulator 300 including a single lamella from a gecko specimen as the seta structure 304 and using the configuration shown in Figures 16A and 16B has been used to pick-up an 30 object as heavy as 5.2 grams. Also, two or more manipulators may be used simultaneously to manipulate even heavier objects.

Additionally, it has been found that a parallel adhesive force of a seta structure can be increased by sliding the structure parallel to an engaged surface. This so-called velocity effect can be used to increase grip and to respond to 5 larger perturbations in movement of, for example, a manipulator.

As shown in Figure 17, for a manipulator including a gecko setal array engaging a glass substrate or plate and moving at a velocity of about 3mm/s, the parallel adhesive 10 frictional force approaches approximately 30 grams. Also, the kinetic friction peaks (region A) and stabilizes above the static limit (region B). This means that the force is actually greater when the seta structure is moving as opposed to remaining stationary.

15 Moreover, as shown in Figure 18, when a manipulator is pulled rapidly up to about 6 mm/s, various gecko setal array structures produce linearly increasing adhesive forces. That is, the adhesive force increases as the array slides faster and the relationship between force and velocity is 20 significantly linear.

Thus, while van de Waals dry adhesion occurs at the level of individual setae, the integration of thousands of these setae can yield complex-even fluid-like-dynamics at the macroscopic scale. Using this dynamic response in arrays of 25 setae, adhesion may be maintained during large, rapid perturbations. Force can be maintained and indeed increased when sliding occurs. Moreover, this velocity effect suggest that attachment of a setal gripper can be more effectively accomplished if the motion is rapid.

30 Those skilled in the art will recognize that the adhesive microstructures of the invention may be utilized in a variety

of ways. For example, the technique of the invention can be used in pick and place micromanufacturing, micromanipulation, and microsurgery applications. For example, a seta can be attached to a micromanipulator to pick up a fiber optic, move 5 it, and put it down again. Other uses include manipulating retinal prosthesis implants/explants, attaching to nerves during surgery, and pick and place of silicon wafers or disk drive components.

The setae of the invention may also be used as clutch 10 mechanisms in micromachines. Since setae adhere in a directional manner, a seta could be used as a clutch mechanism similar to a ratchet, but on a smooth surface.

Other applications for the technique of the invention include: insect trapping, tape, robot feet or treads, 15 gloves/pads for climbing, gripping, etc., clean room processing tools, micro-optical manipulation that does not scar a surface and leaves no residue or scratches, micro-brooms, micro-vacuums, flake removal from wafers, optical location and removal of individual particles, climbing, 20 throwing, and sticker toys, press-on fingernails, silent fasteners, a substrate to prevent adhesion on specific locations, a broom to clean disk drives, post-it notes, band aids, semiconductor transport, clothes fasteners, and the like. In many of these applications, patches of spatula on a 25 planar substrate are used, as opposed to patches of spatula positioned on a shaft.

The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled 30 in the art that the specific details are not required in order to practice the invention. Thus, the foregoing descriptions

of specific embodiments of the present invention are presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, obviously many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the following claims and their equivalents.